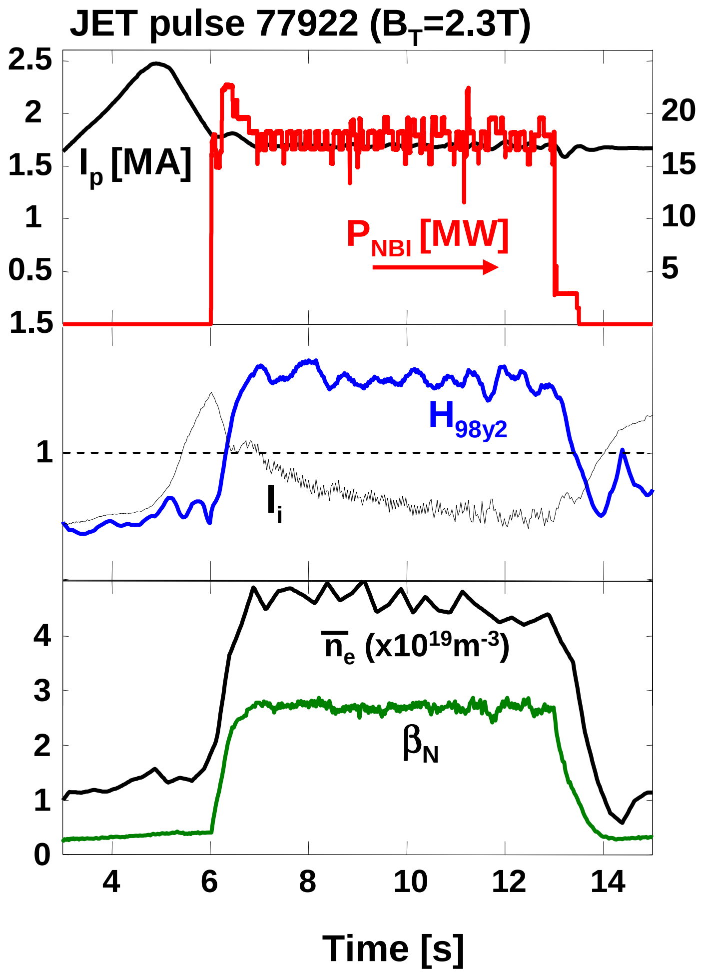
JET hybrid regime: requests for modelling

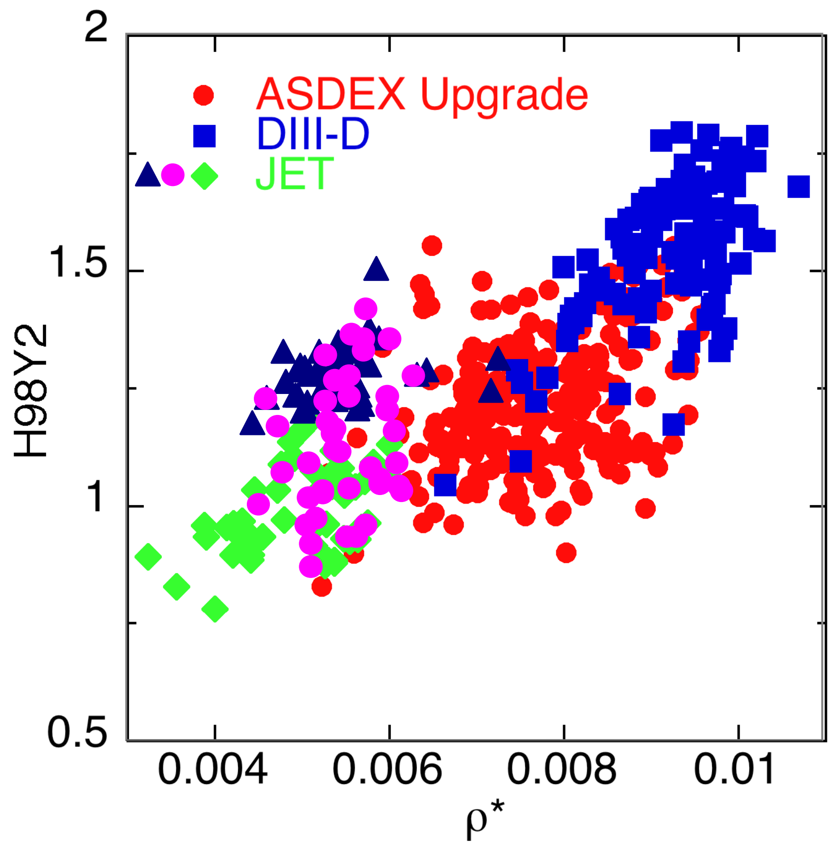
E. Joffrin

with thanks to J. Hobirk, J. Citrin, J Garcia, D. McDonald, C. Challis, J. Lonnroth

ITM meeting 13th September 2010

Hybrid scenario development at JET.



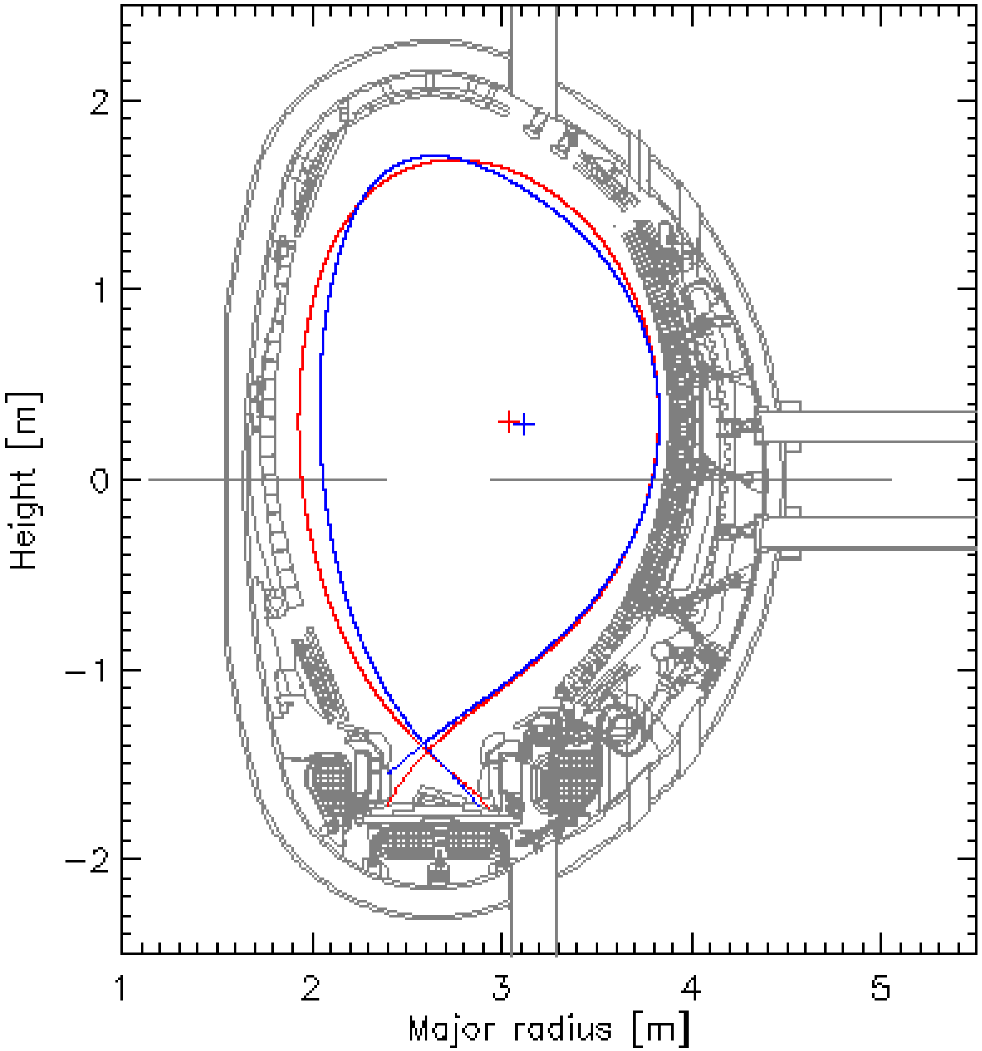


E. Joffrin IAEA 2008

- ❑ JET has produced high confinement discharge at different ρ* from 0.004 to 0.007.
- ❑ The bulk of the data are now in line with the AUG dataset: same H98y2 for smaller ρ*.
- ❑ This has been achieved for both low and high shape.

Plasma shapes used in hybrid scenario

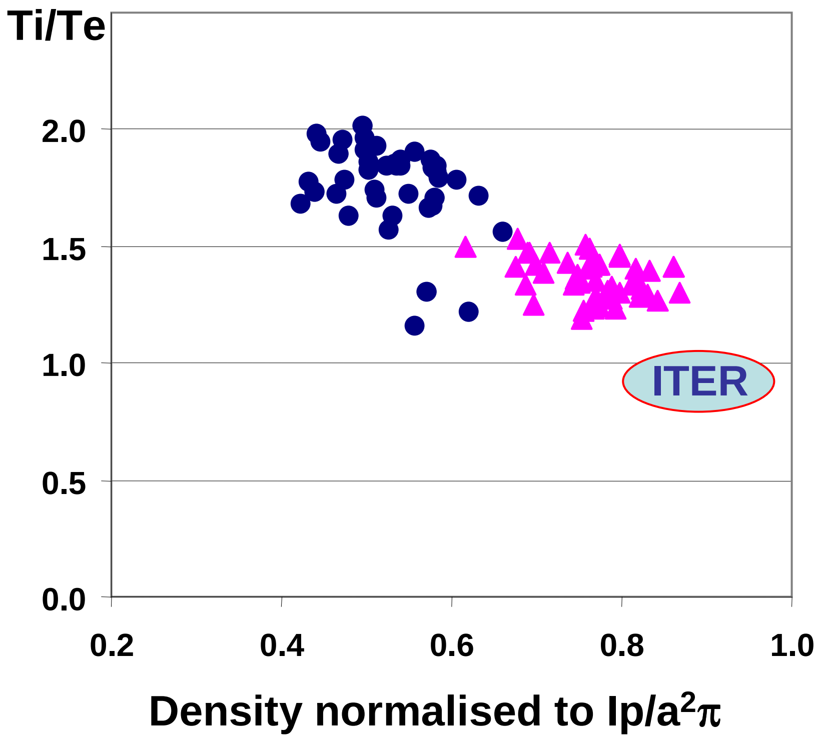
- Use low triangularity (δ≈0.2) D1Z_VC_OS_LT scenario and high triangularity (δ≈0.4) HI_BPOL_LO_PFX scenario.
- Proposal was to begin the q profile exploration with the low shape, then to move on to the high shape.
- Also, the core transport studies (i.e. separation of q and rotation profile) has been executed with the low shape.
- Proposal was to perform power scans in Hybrid and H-mode references at low and high shape.
- Important focus: collecting ETB data (HRTS, ECE, Li-beam) to study its impact on global confinement.

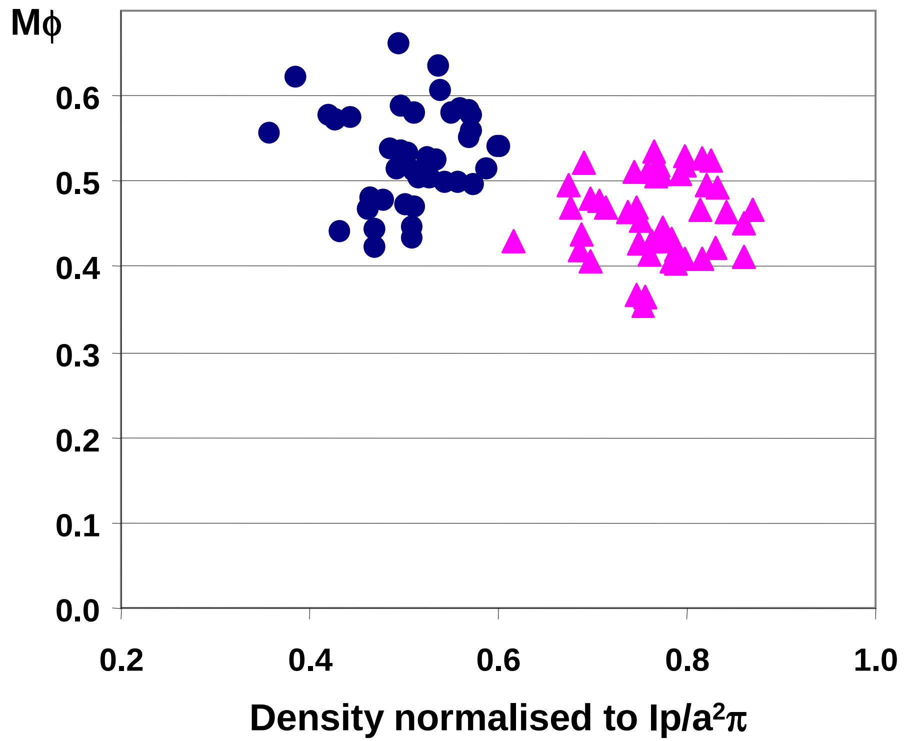


D1Z_VC_OS_LT

HI_BPOL_LO_PFX

Operational range in Ti/Te & Mach number

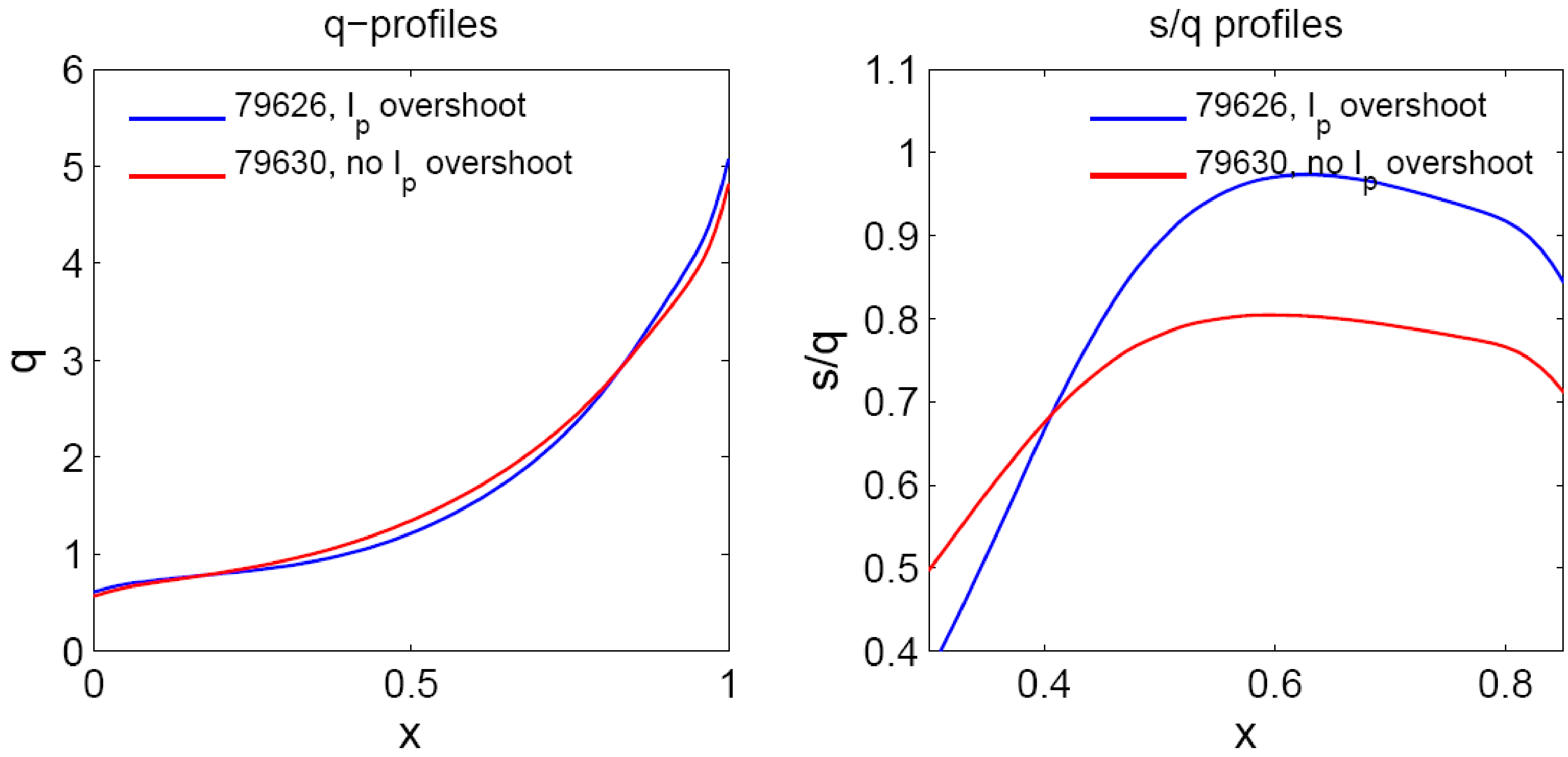




- ❑ Hybrid have been developed with the high shape and low shape in separated domains of Ti/Te and rotation but with very similar q profiles.
- ❑ The pedestal pressure is the main reason that explains the difference.

Role of Ip overshoot on core transport

How is the change of q profile affecting the core transport when the ITG physics is assumed



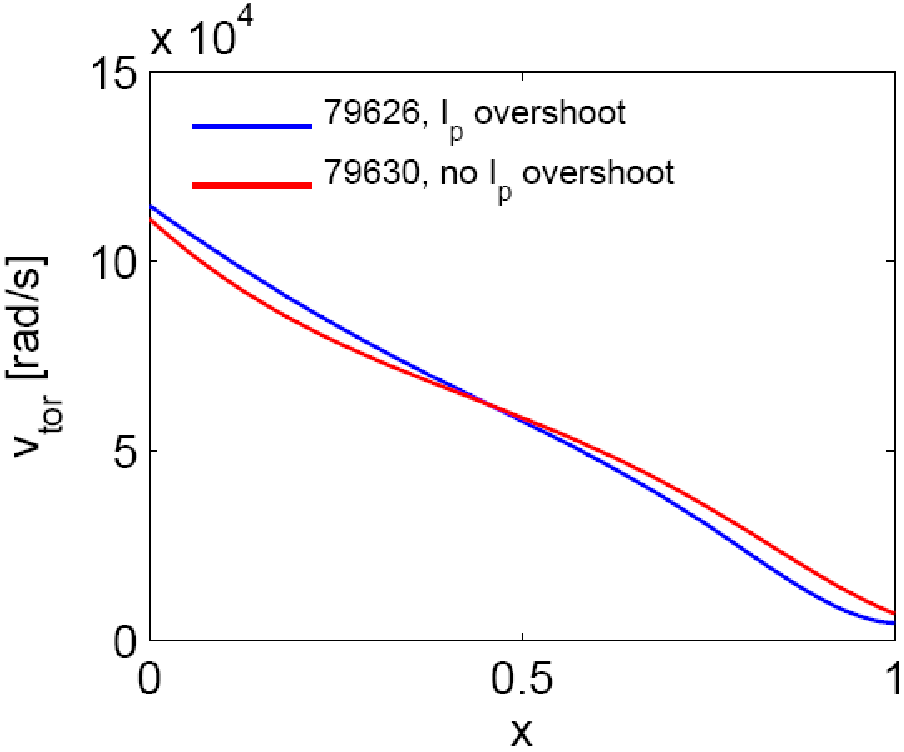
H98=1.19

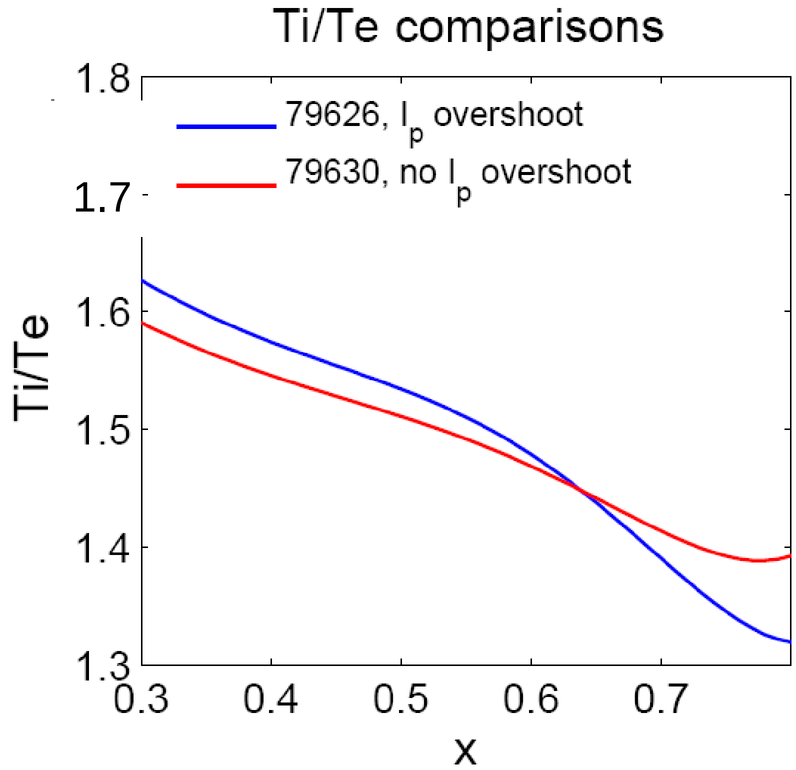
H98=1.06

- **Broad q profile could have a beneficial effect on the 1+2s/q term of the critical gradient length for ITG: it would increase from 2.6 to 3.**

Citrin 2010

Role of Ip overshoot on core transport

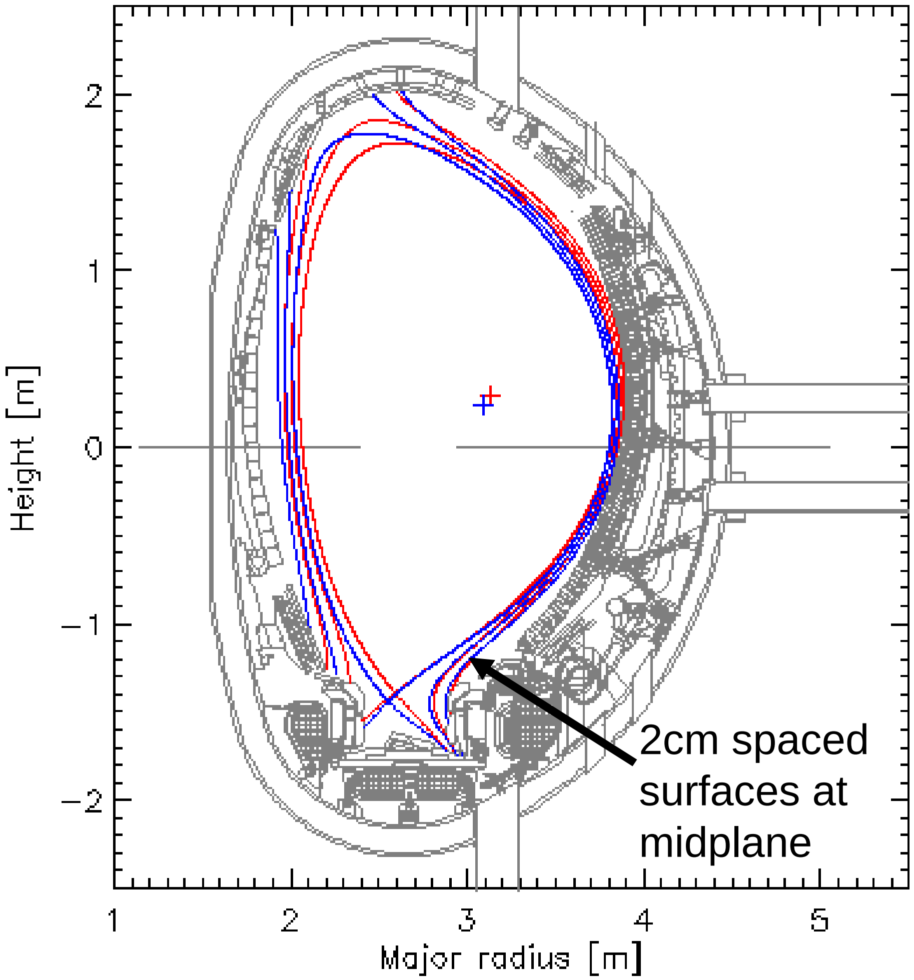




- This is done assuming that Vtor and Ti/Te are constant (within the error bars and could possibly explain the confinement difference of ~10% between the two pulses.
- Decoupling the different contributions (Ti/Te, rotation, s/q) is probably a too challenging task for modelling and the diagnostic accuracy.

Edge – core integration

High shape, 1.4MA/1.7T, H-mode



away from roof - HI_BPOL_LO_PFX

close to roof – HT3

	d (cm)	a (m)	R (m)	κ_a	δ_U	δ_L
new	3.5	2.93	74.5	1.59	0.37	0.39
HT3	1.6	2.95	73.4	1.56	0.52	0.40

NB: d is top-LCFS distance on mid-plane

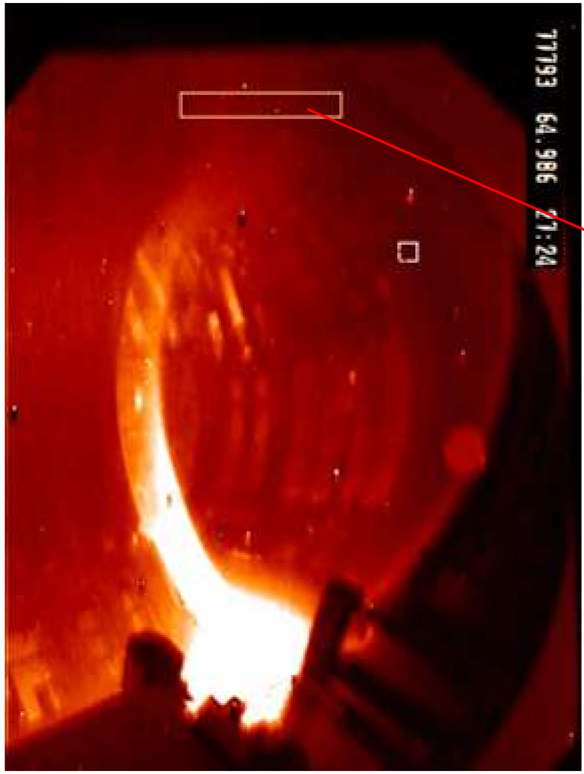
$$\tau_{98(y,2)} \propto \kappa_a^{0.78} R^{1.39} a^{0.58}$$

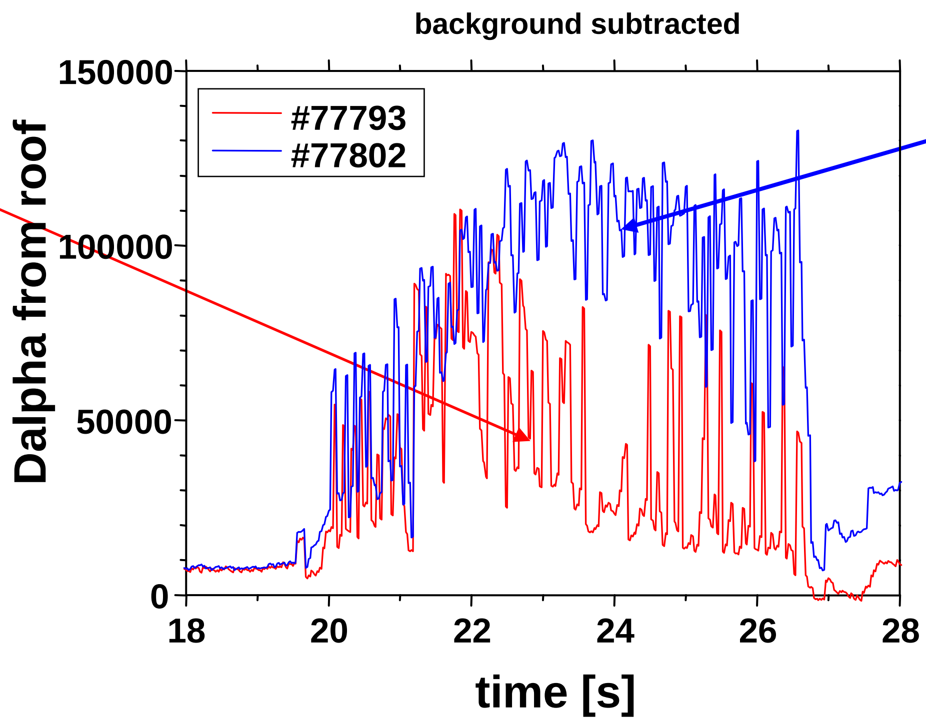
so if τ_E stayed same

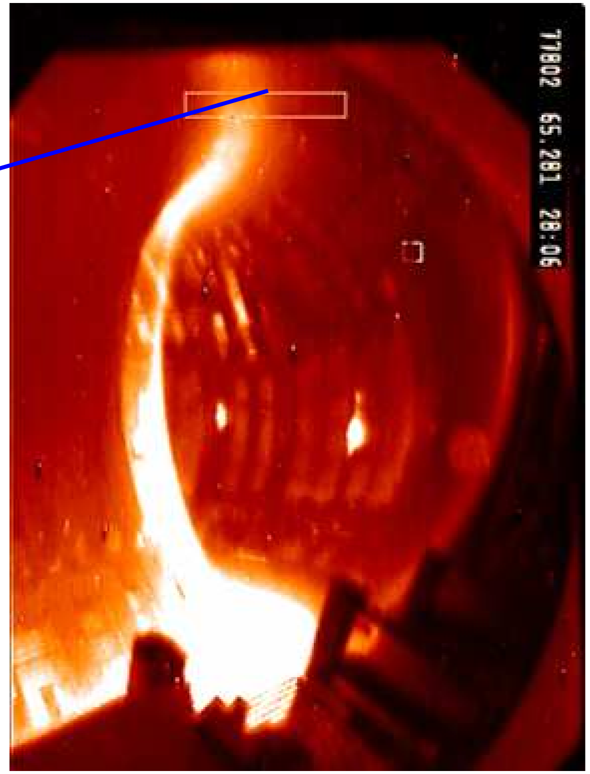
$$\frac{H_{98(y,2),HT3}}{H_{98(y,2),HI\_BPOL}} \approx 1.01$$

➔ H98(y,2) scaling predicts similar confinement for the two shapes

Edge – core integration







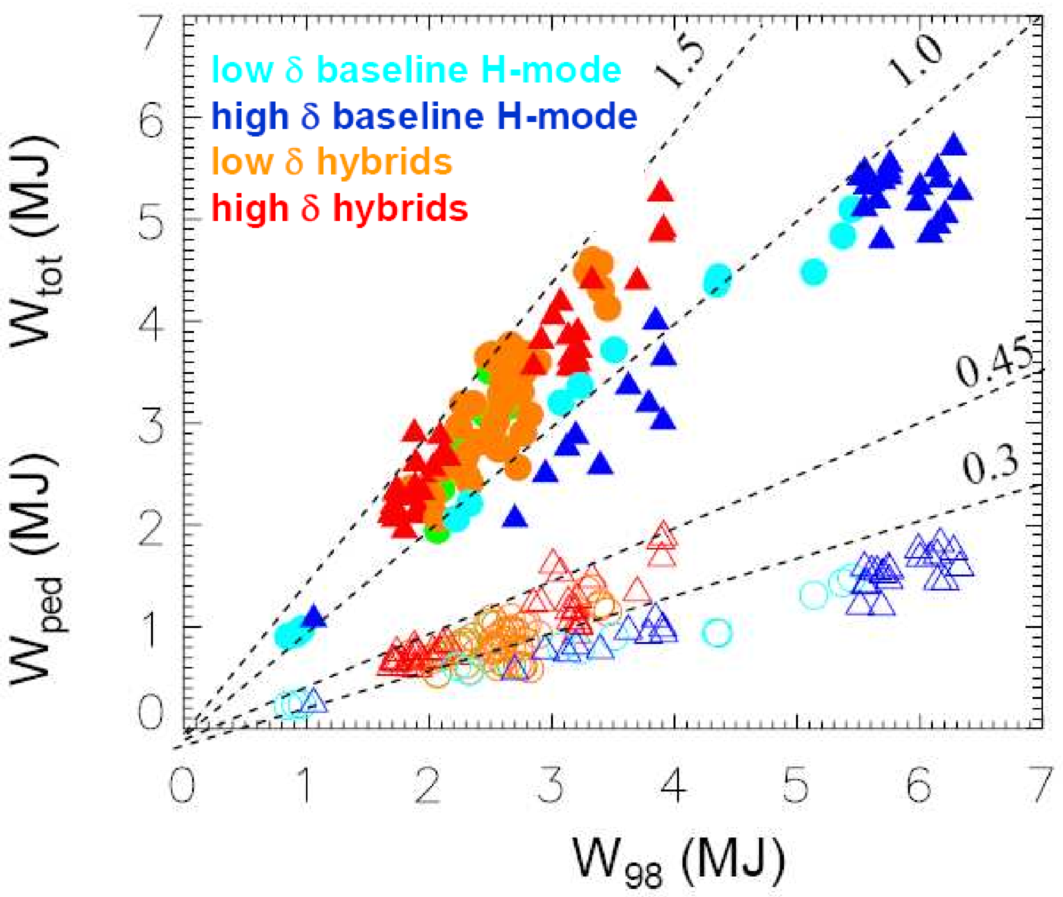
$H98_{y2}$=1.3

Both pulses have the same Ip, B_T, density and β_N

$H98_{y2}$=1.15

- ❑ Modelling with EDGE2D is on-going to understand the impact of the neutral flux on the edge temperature and density profiles 10cm inside the separatrix.
- ❑ This effect WILL be very different in an all metallic machine with Be/W. Therefore edge-core integration is essential for the optimisation of the pedestal confinement

Comparison of pedestal behaviour between hybrid scenario and baseline

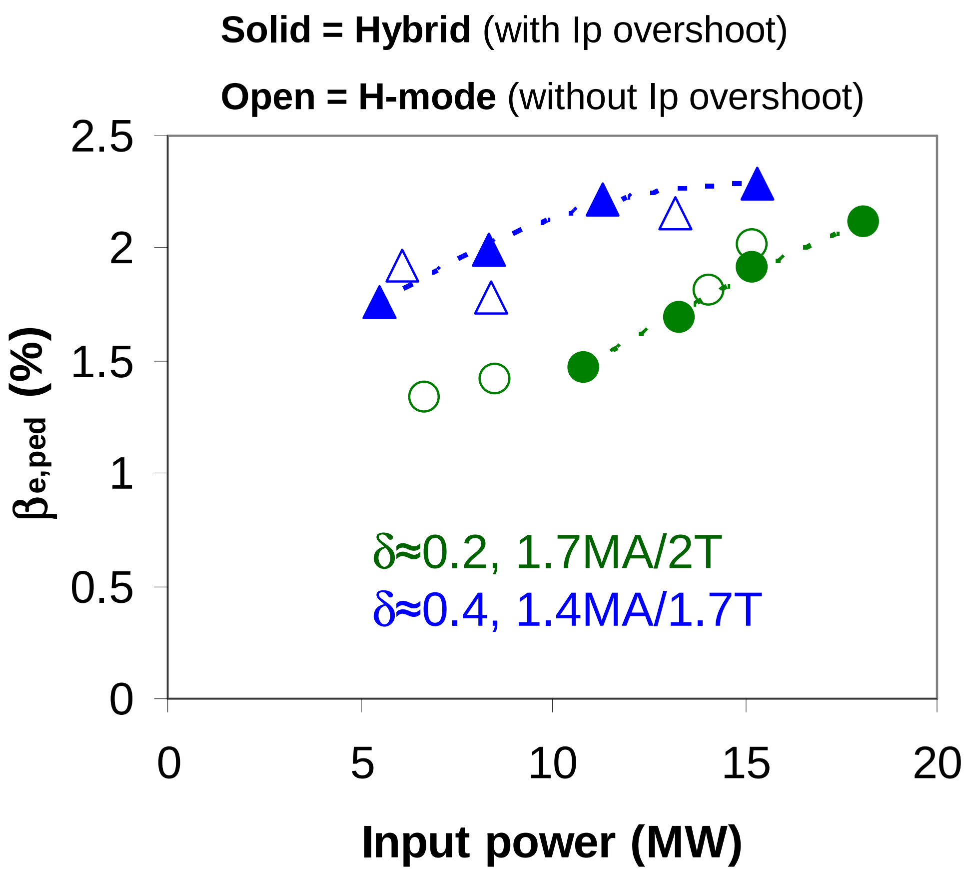


L. Frassinetti EPS 2010

- ❑ In JET, hybrids appears to have a higher pedestal energy at fixed W98 than the baseline scenario.
- ❑ High d hybrids have higher energy in the pedestal than low shape hybrids
- ❑ Please note that the hybrid and the baseline are not using the same plasma shape. This may impact on the comparison between baseline and hybrid scenario.

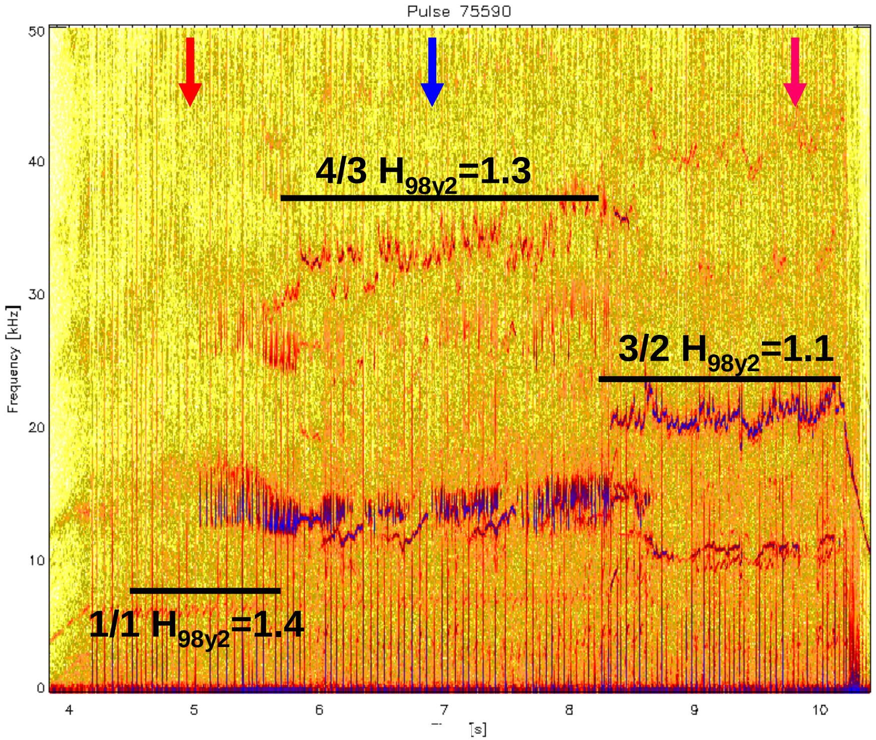
Pedestal physics & modelling

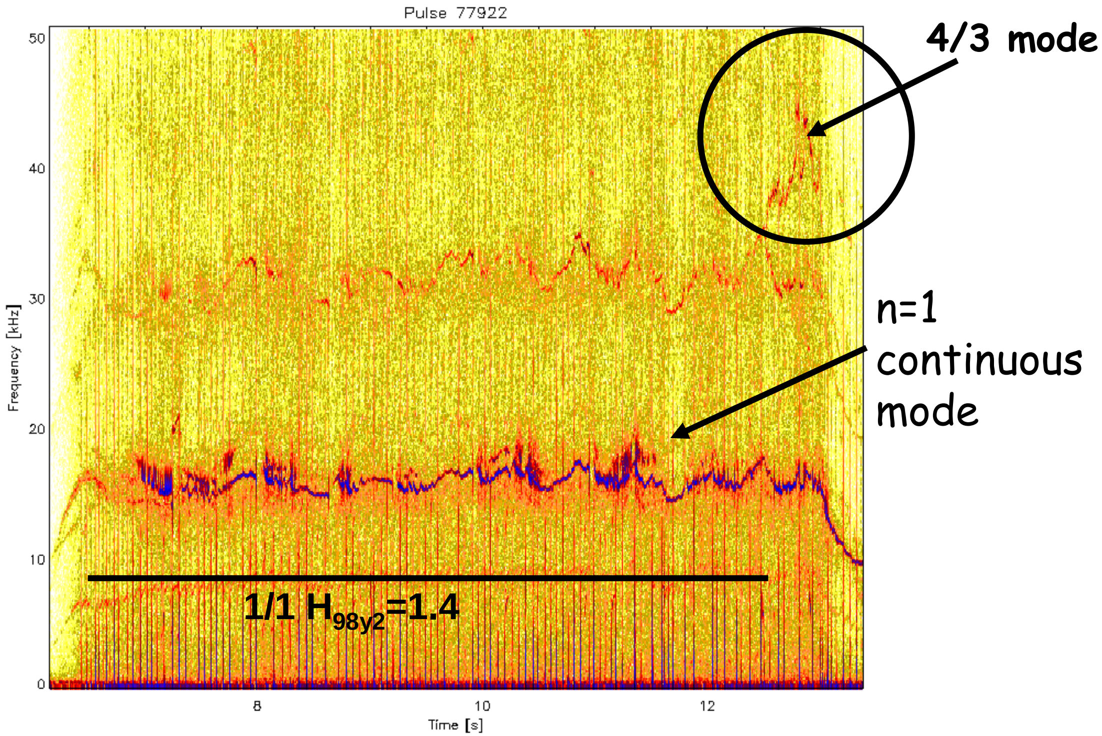
- Across low and high shape scans; T_e, p_e and β_e at the pedestal top increase with power.
- Again, H-mode and Hybrid datasets agree well for the same shape
- Low shape $\beta_{e,ped}$ rises continuously with power, whereas high shape $\beta_{e,ped}$ is higher and appears to saturate with power.
- Consistent with the trend seen in 2003-6 data suggesting confinement scaling more favourable with β at low shape.
- **Modelling would show if this can be associated with the standard MHD ETB stability model.**

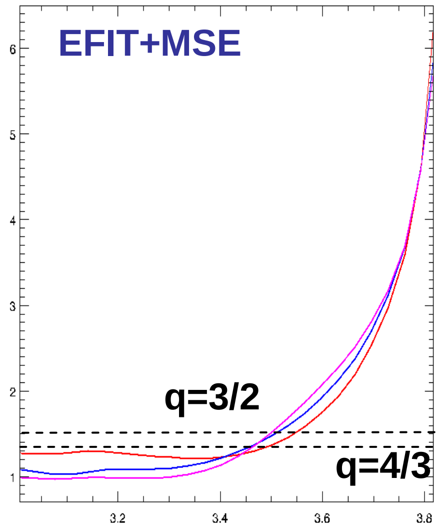


McDonald H-mode WS 2009

Typical MHD modes in hybrids

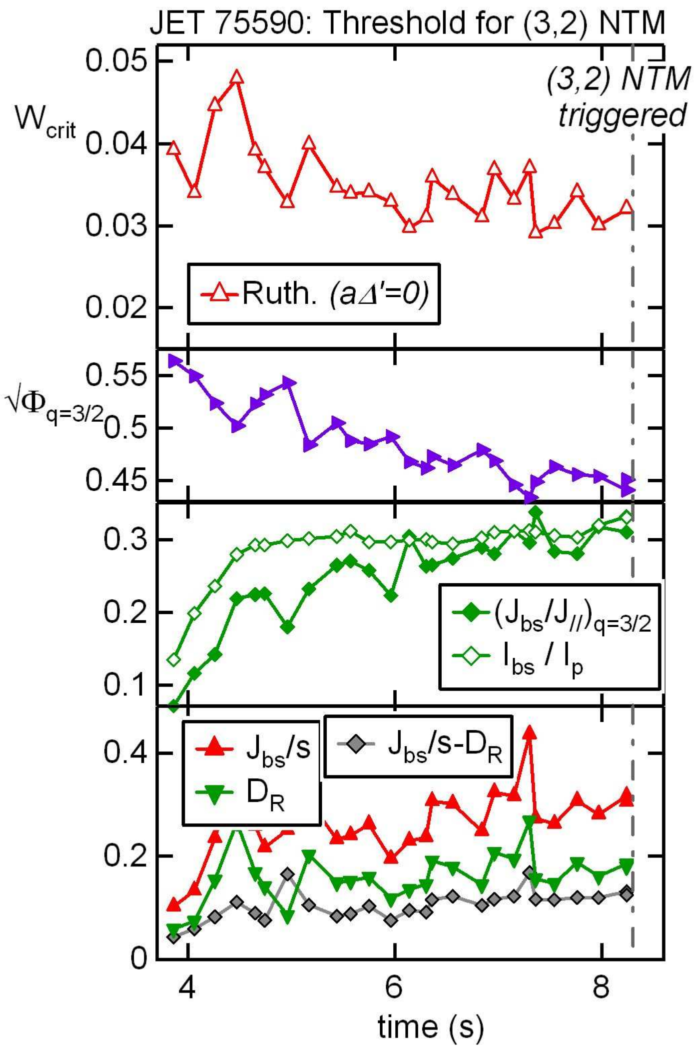






- Depending on the initial conditions (target q), the hybrid scenario can be hit successively by 5/4, 4/3 and then 3/2 modes during the current diffusion phase, or have very mild MHD activity.
- Each of these modes are affecting the confinement. Stable plasma are often characterised by a continuous n=1 mode with infrequent sawteeth.
- Maintaining broad q profile appears to be a necessary condition for the stability of the hybrid scenario and its confinement performance.

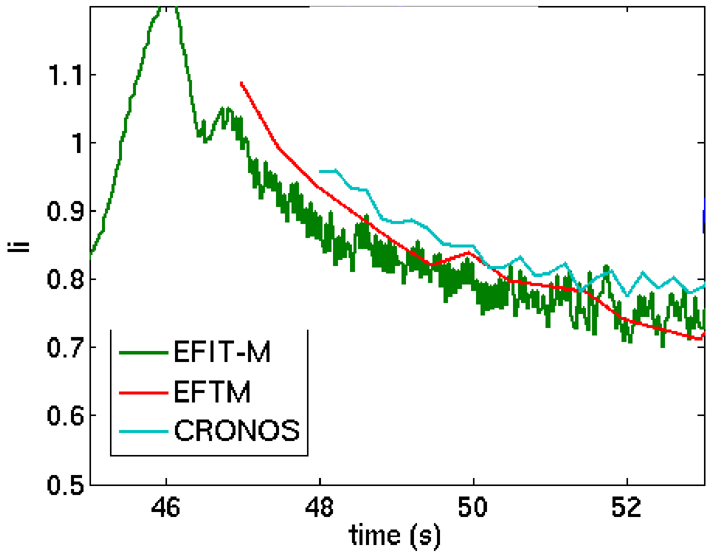
Evolution of the critical island 3/2 width calculated with XTOR (without rotation).



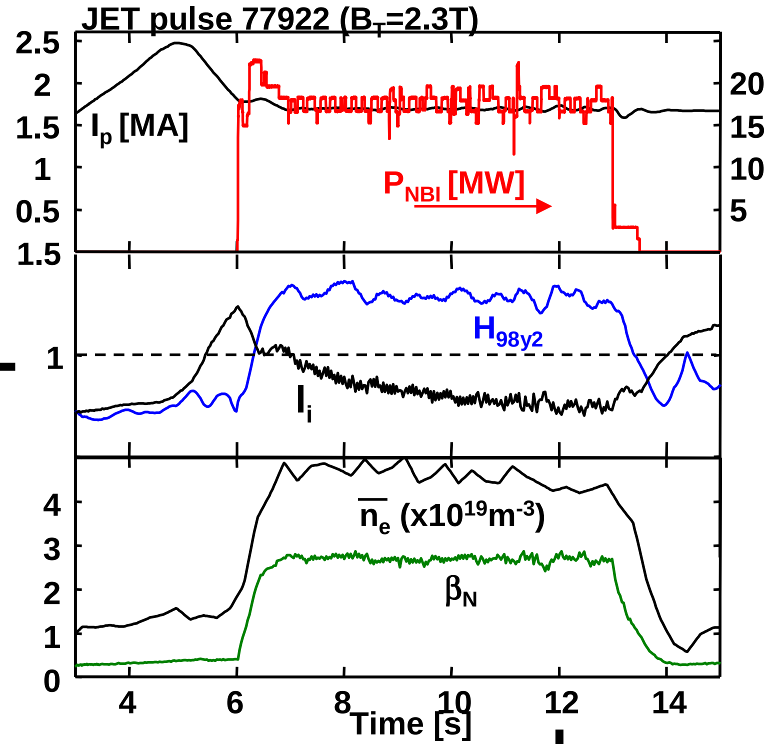
P. Maget IAEA 2010

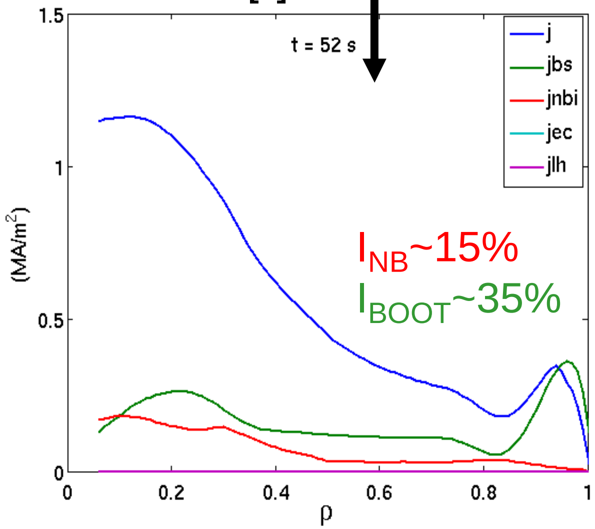
- ❑ Critical island width very dependent on local magnetic shear at q=3/2 and decreases with time.
- ❑ The 3/2 surface moves also towards the plasma centre where the pressure gradients are larger.
- ❑ As a results there is a trend toward an increase of the bootstrap current with time, so that even if the threshold Wcrit was not changing the plasma is more vulnerable to a given seed at t=8.24s.
- ❑ The stabilising term D_R (curvature) on the other hand does not vary substantially.

Current balance in hybrid scenario



J. Garcia 2010

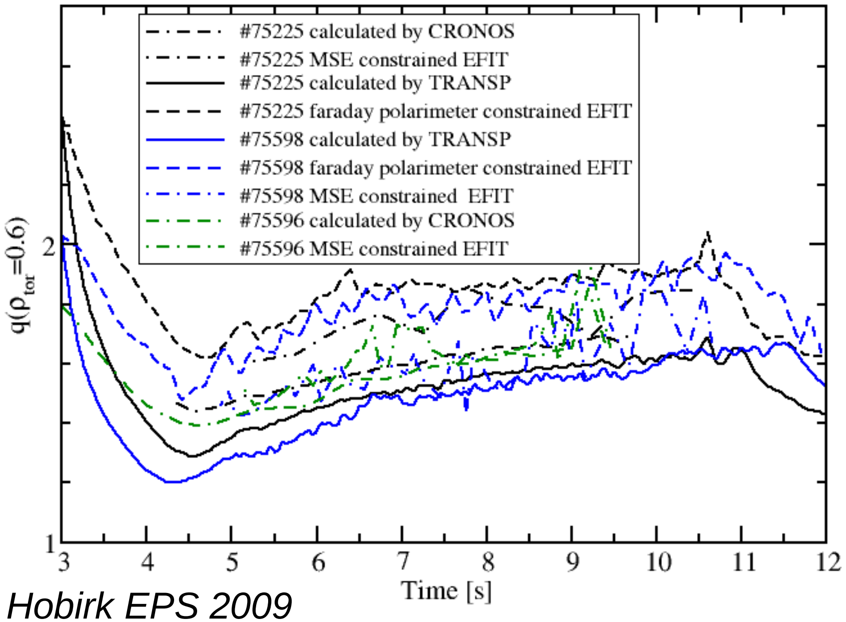




- ❑ Current evolution in hybrid scenario looks consistent with neoclassical modelling (CRONOS) during the whole high confinement phase (H~1.3).
- ❑ Current balance showing that stationary condition have been reached at the end of the heating pulse with high confinement

Has JET a current anomaly like in AUG & DIII-D?

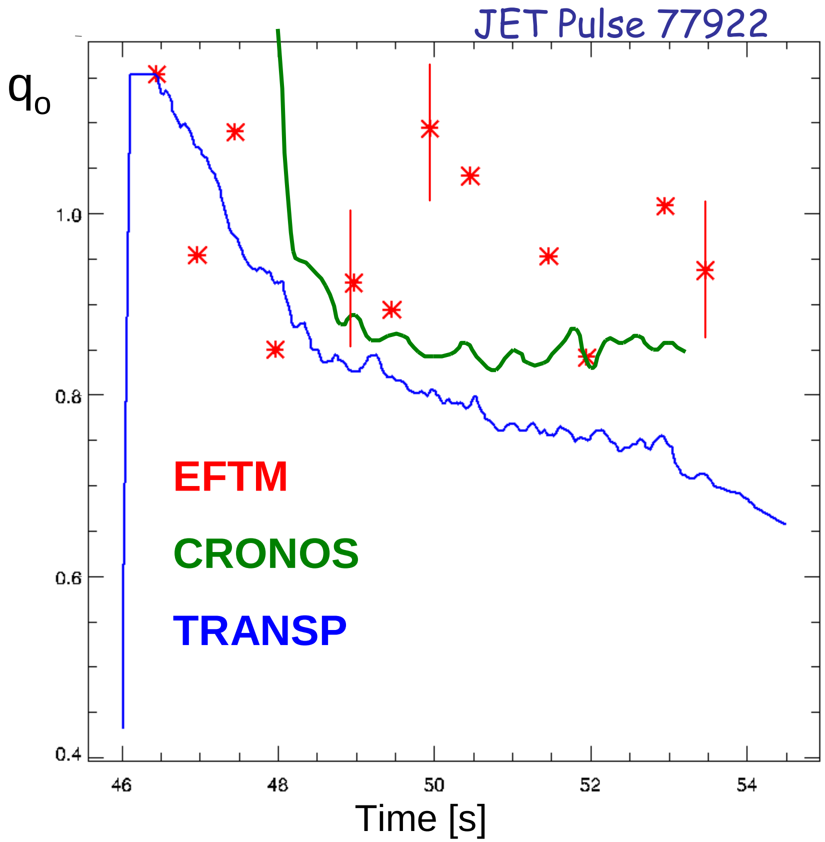
q time evolution at ρ_{tor}=0.6



J. Hobirk EPS 2009

Current diffusion anomaly reported in AUG and DIII-D.

- ❑ JET follows classical current diffusion from both CRONOS and TRANSP.
- ❑ Confinement improvement appears to survive q-profile change

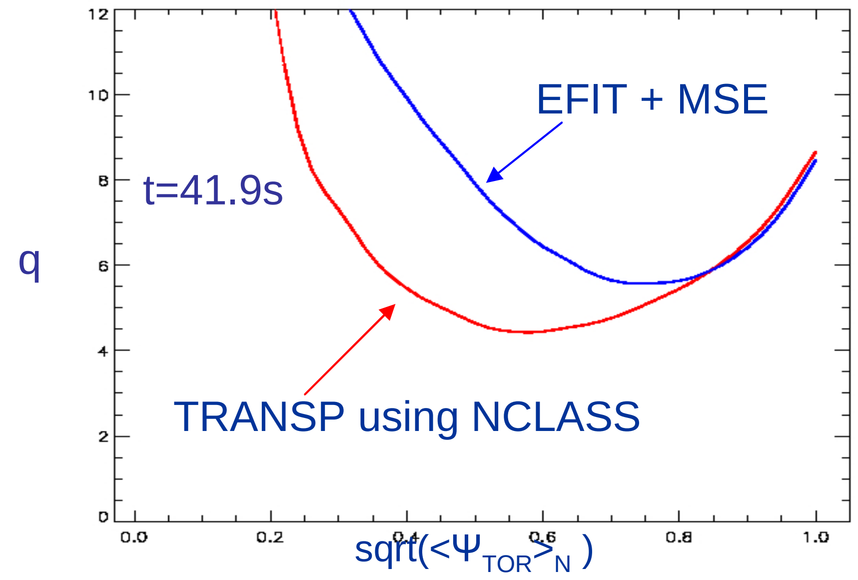


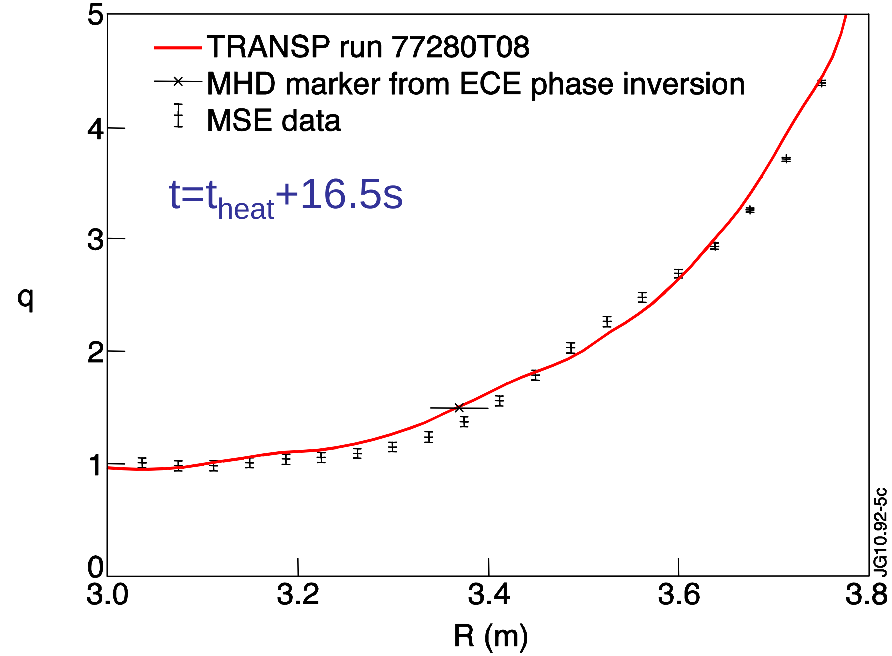
Is that general? Not sure with 77922 + n=1 continuous mode. It is possible that the n=1 kink activity clamps the core q profile to 1.

➔ Improve measurements statistics with and without the n=1 mode.

➔ Introduce in current diffusion modelling the effect of the flux redistribution by the n=1 mode.

Current Ramp Modelling for JET AT regimes



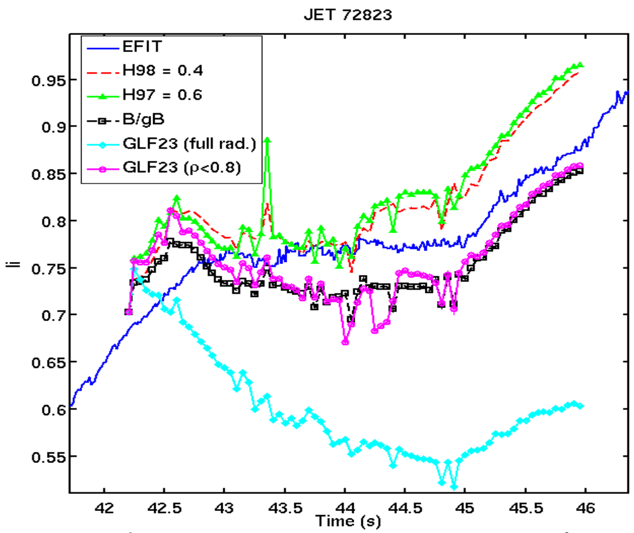


- #76949 – MSE data taken during current ramp (41.5-41.9s)
- After 0.3s of modelled neo-classical current diffusion NCLASS model has diffused current into centre too rapidly compared with measurement from MSE
- This contrasts with agreement between MSE measurement and modelling using initially MSE measured q-profile and then resistive current diffusion for hybrid plasma (#77280) with heating phase extended to 3 resistive times reaching stationary conditions
- Ohmic ramp-up phase appears non-neo-classical – possible link with high electron collisionality ν_e?

I. Jenkins EPS 2010

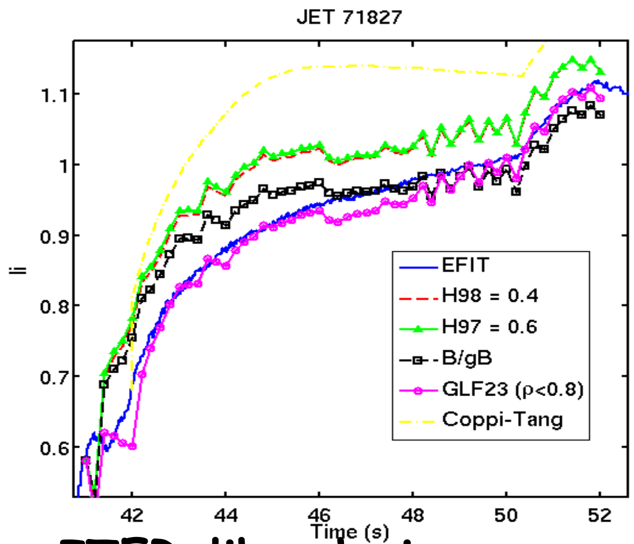
Validation of heat transport models for current ramp-up

- Heat transport models for current ramp-up validated on a database of shots from JET, Tore Supra, and AUG, ohmic or moderate heating (LHCD, ECCD, NBI, ICRH)
- Current + heat transport, prescribed plasma boundary
- Agreement on li chosen as the main figure of merit
- Various heat transport models tested: scaling-based models, Bohm/gyro-Bohm, GLF23, Coppi-Tang
- Bohm/gyro-Bohm and scaling-based models provide agreement on li within +/- 0.15 on JET and Tore Supra dataset



Steady state scenario ohmic ramp-up (2.7T, 1.8MA)

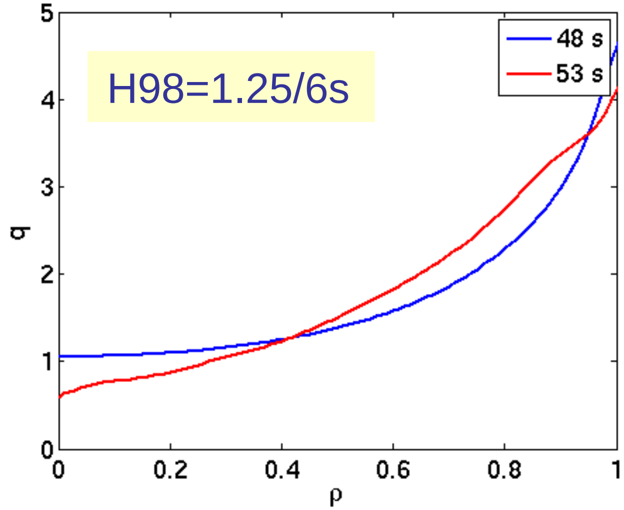
[F. Imbeaux al IAEA-FEC 2010]

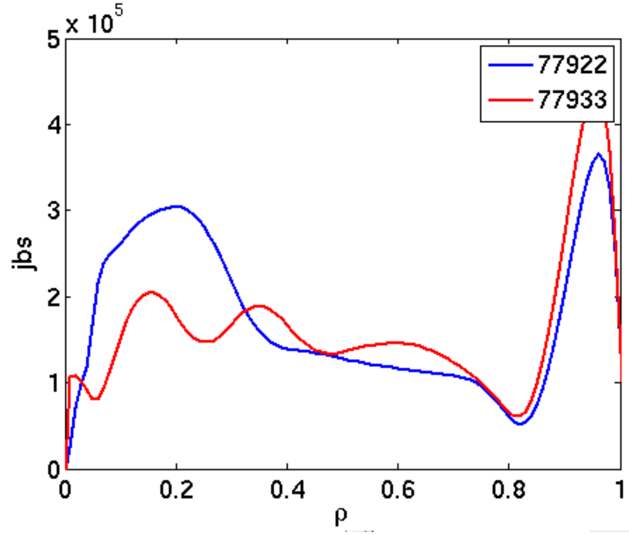


ITER-like ohmic ramp-up (2.6T, 2.5MA)

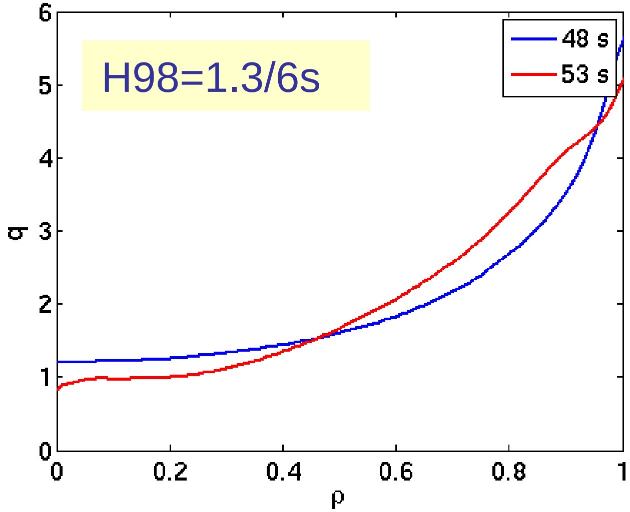
Current balance in stable hybrid scenarios

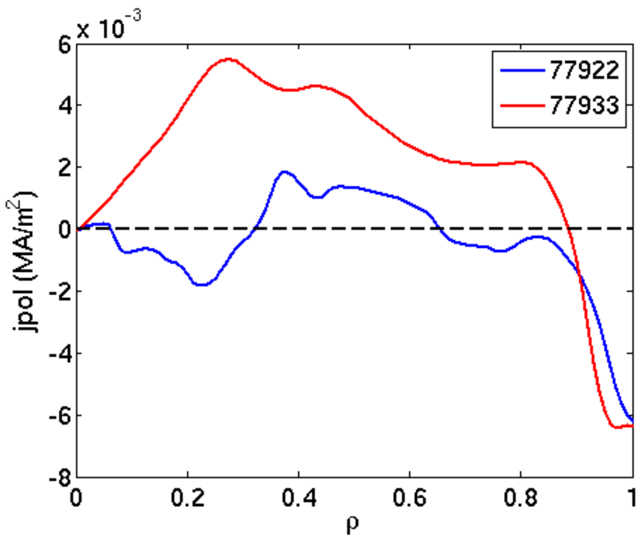
77933@t=52s (2.3T, 2MA), no MHD





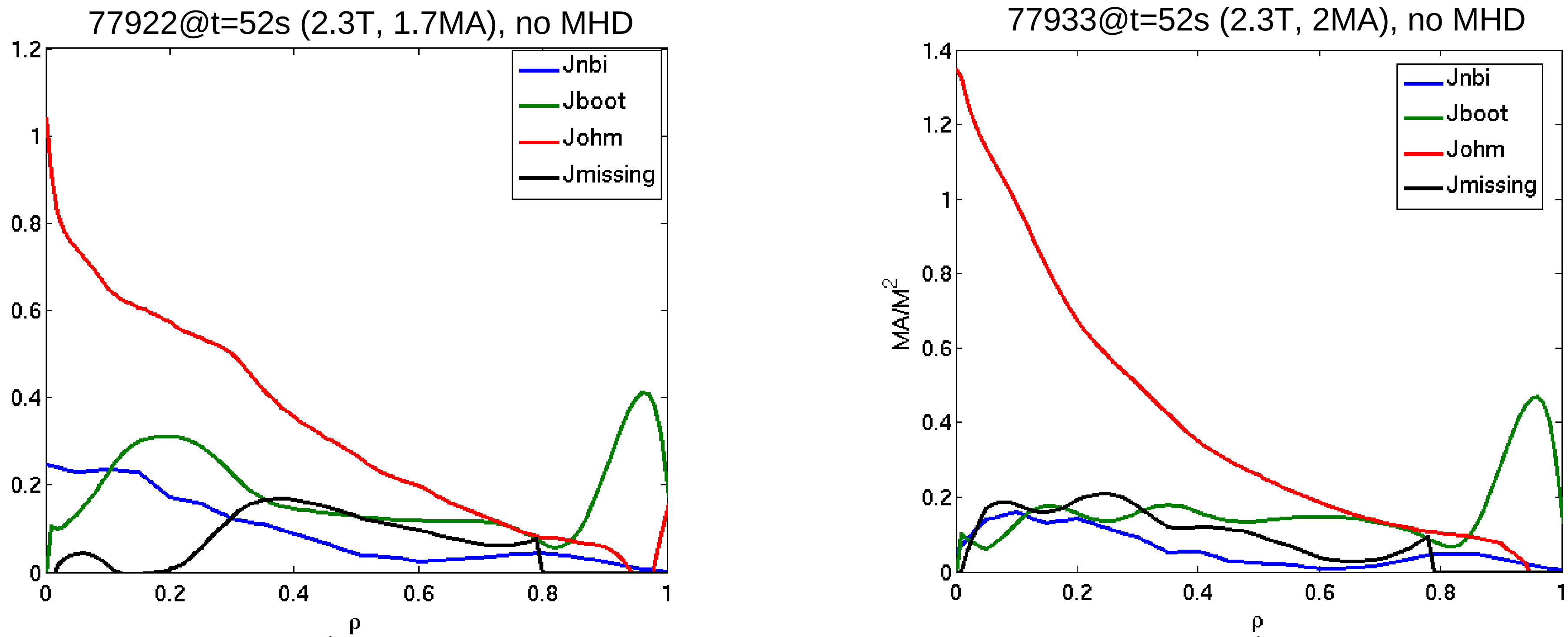
77922@t=52s (2.3T, 1.7MA), no MHD





- ❑ Bootstrap current is not significantly changed when the total current is increased.
- ❑ q profile diffuses faster for the high current case.
- ❑ The poloidal current can be used as a marker to determine the optimum point for the hybrid scenario in terms of stationary conditions (see next)

Missing non-inductive current



$I_{missing}$=190 kA ; q_{95}=4.3

$I_{missing}$=270 kA ; q_{95}=3.8

J. Garcia PRL 2010

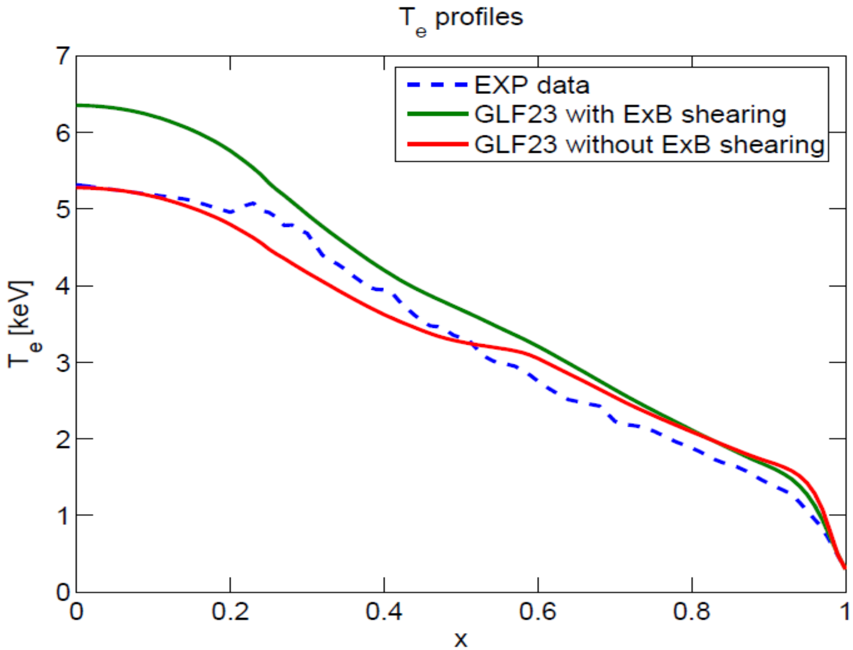
$$\mathbf{j}_\theta = 0 \Rightarrow F' = 0 \Rightarrow j_\varphi = RP' = \varepsilon^{-1/2} j_{bs}$$

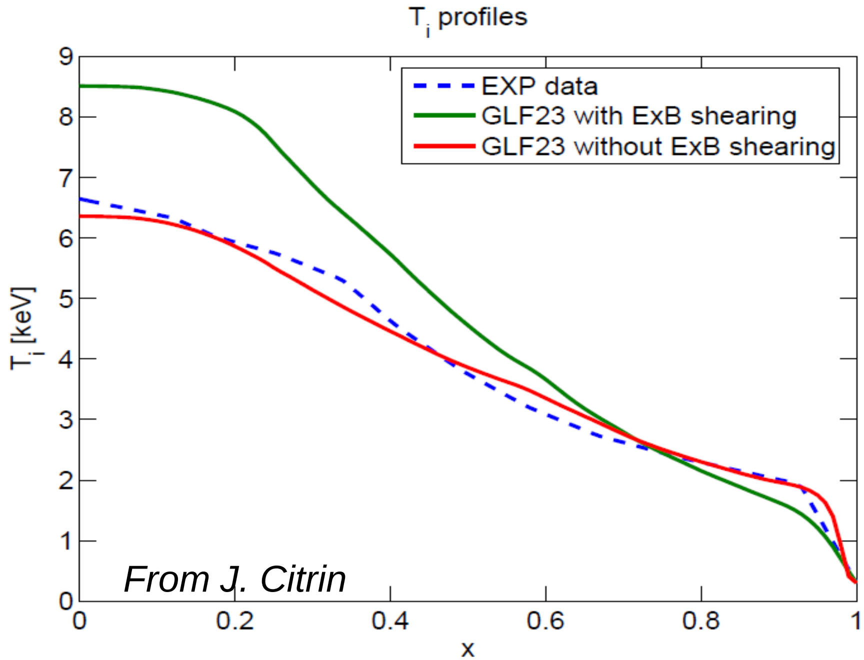
$$j_\varphi = j_{bs} + j_{ohm} + j_{cd} \quad \Rightarrow j_{CD} = j_{bs}\left(\frac{1-\varepsilon^{-1/2}}{\varepsilon^{-1/2}}\right) - j_{ohm} = j_{missing}$$

To achieve stationary hybrid scenario

- **Defines a condition for current alignment and CD deposition from external sources in hybrid**
- **Off-axis current would be essential for maintaining this regime on more the $3\tau_R$**

Transport analysis using the ITG model

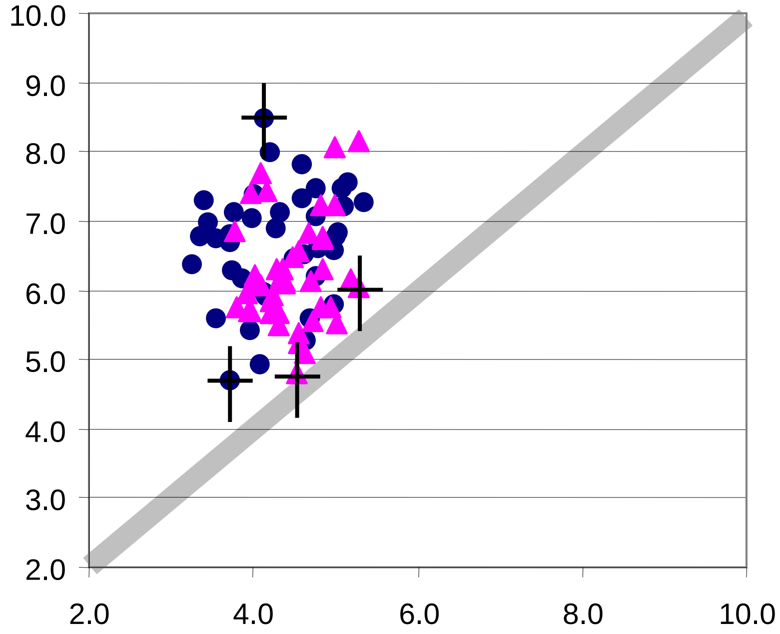




- The comparison of experimental profiles (dashed) and GLF23 prediction with and without ExB shear stabilisation for pulse 77933 Te (experimental data from Thomson scattering) and Ti (charge exchange spectroscopy), shows that GLF23 does not reproduce the data when rotation is included.
- The physics of the threshold might be incomplete for these type of pulses

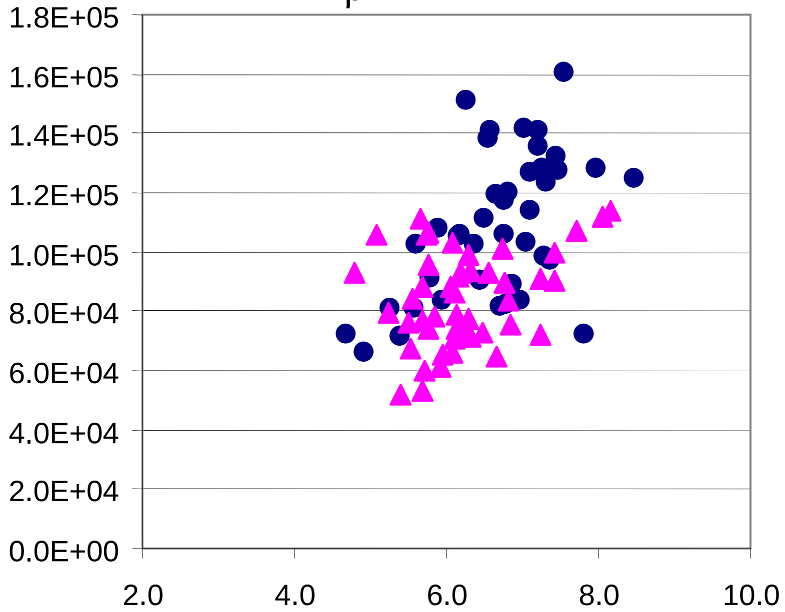
Transport in high and low density & rotation hybrid

R/LTi experimental



R/LTi Theo (normalised to GS2 calculation from 74637-38)

Grad (ω) All data at ρ~0.5 toroidal coordinate

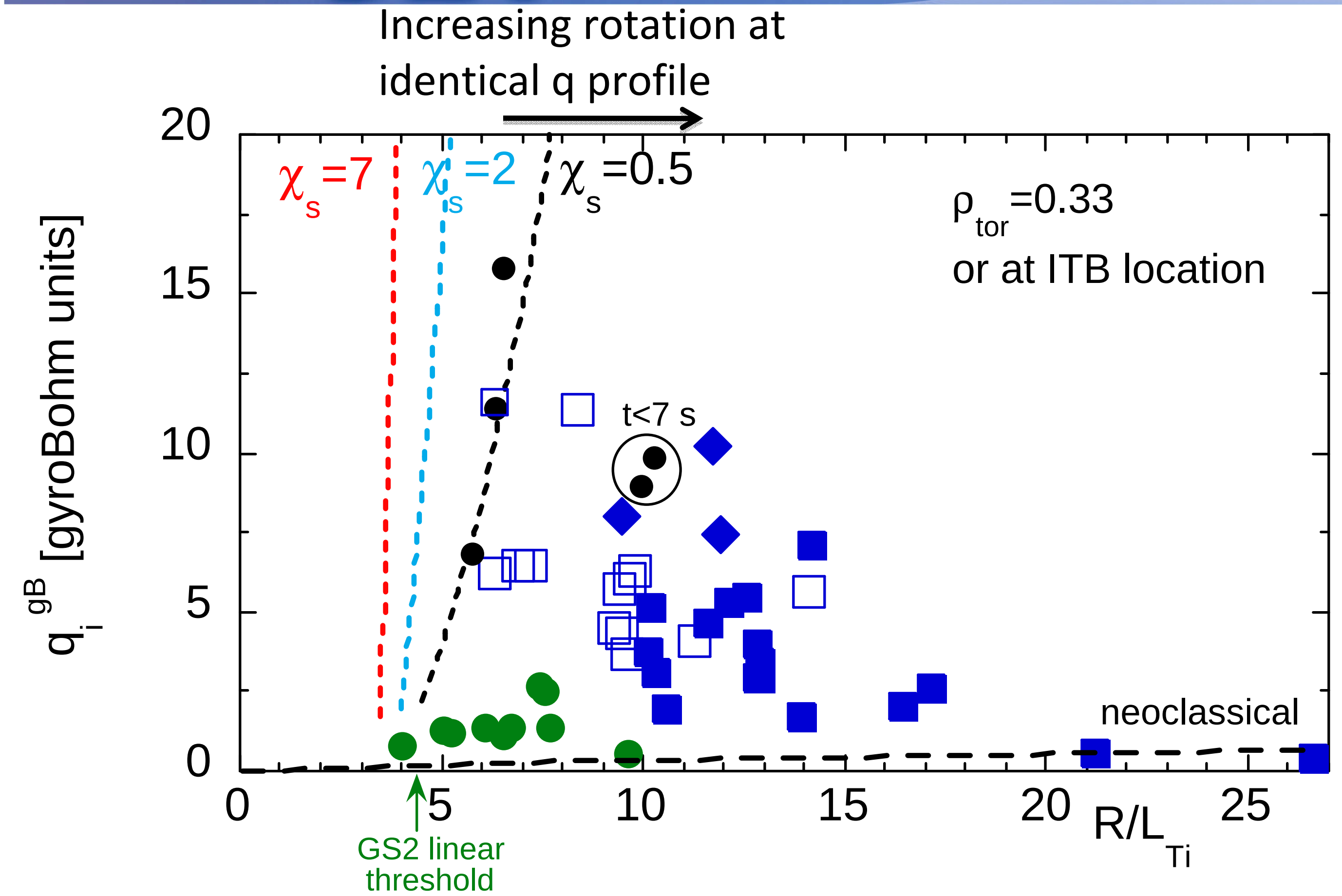


R/LTi experimental

1- Both high shapes and low shapes are above the critical gradients normalised to GS2 values for 4 points. Low shape are showing higher R/L_{Ti} than high shapes in general.

2- Gradient of rotation is higher for low shapes than high shapes. There is also a trend suggesting an increase of R/L_{Ti} with the rotation gradient. This is suggestive to the fact that stiffness in low magnetic shear could depend from the gradient of rotation.

Reduced core ion transport in hybrids and ITBs in presence of low magnetic shear and high rotation

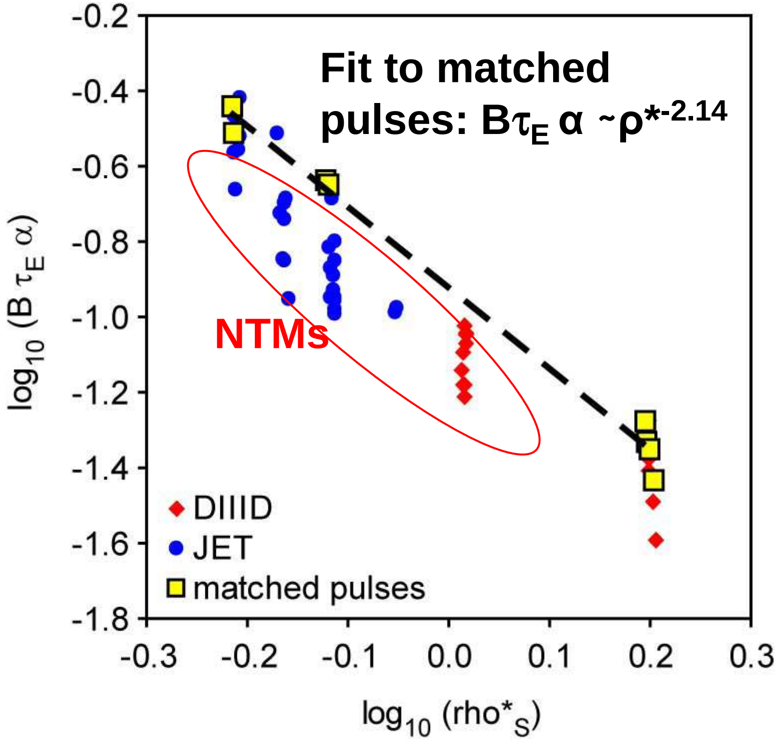


Blue= ITBs
Green=hybrids
Black=L-mode q profile scan at high rotation, with low magnetic shear for t<7 s

[P. Mantica et al IAEA-FEC 2010]

ITBs and hybrids achieve high R/L_{Ti} but mostly remain in the region of turbulent flux. They can be interpreted in terms of a progressive reduction of ion stiffness, allowing to exceed significantly the ion threshold. This picture allows the same physics interpretation of the behaviour of core ion heat transport in operationally different regimes.

Extrapolation to ITER



Challis APS 2009

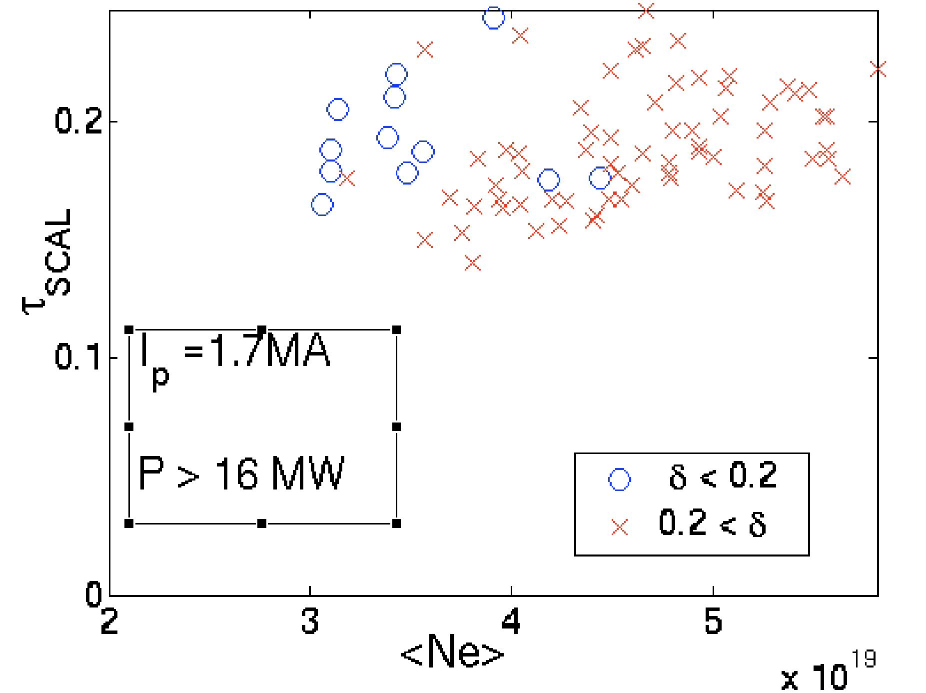
The hybrid work has revealed that the IBP98y2 scaling cannot be used in its present form:

- ❑ Since plasmas in the hybrid domain show a global confinement enhancement compared with present scaling with β_{NTH} >2.2, it is not obvious that the dependencies of these scaling can be used to extrapolate hybrid plasma performance to the domain of future devices.
- ❑ H98y2 scaling: $B.\tau_E = \rho^{*-2.69}\ \nu^{*-0.01}\ \beta^{-0.90}\ q^{-3.0}$
- ❑ Derived using a large H-mode database with β_{NTH}<2.
- ❑ Developed with engineering parameters: Ip, B_T, P_{IN}, n, a, R, κ and M. The scaling has not been inferred directly from the physics parameters.
- ❑ Dependencies upon physics dimensionless parameters derived assuming Te=Ti and: $\rho^* \sim (MT)^{1/2}/aB$, $\nu^* \sim qna/T^{-2}$, $\beta \sim nT/B^2$ and $q=q_{cyl}=5BR._k/a^2/Ip$

❑ Recently an identity experiment between JET and DIII-D has pointed out that the dependence in ρ* might be Bohm-like rather than Gyro-Bohm-like. This may also have important consequences on modelling of transport from existing machine to ITER. The 1D analysis also confirms this (IAEA, Politzer)

Other evidences from JET hybrid scenario

By selecting discharges with the same current and "about" the same power, the experimental confinement time does not show any dependence from the density



By doing a least mean square regression of a JET hybrids at high triangularity with the dimensionless variables

$$B.\tau_E \sim \rho^{*-2.07}\ \nu^{*-0.32}\ \beta^{-0.4}\ q^{-1.59}$$

with Ti from charge exchange

$$B.\tau_E \sim \rho^{*-2.35}\ \nu^{*-0.23}\ \beta^{-0.16}\ q^{-1.16}$$

with Teff from W

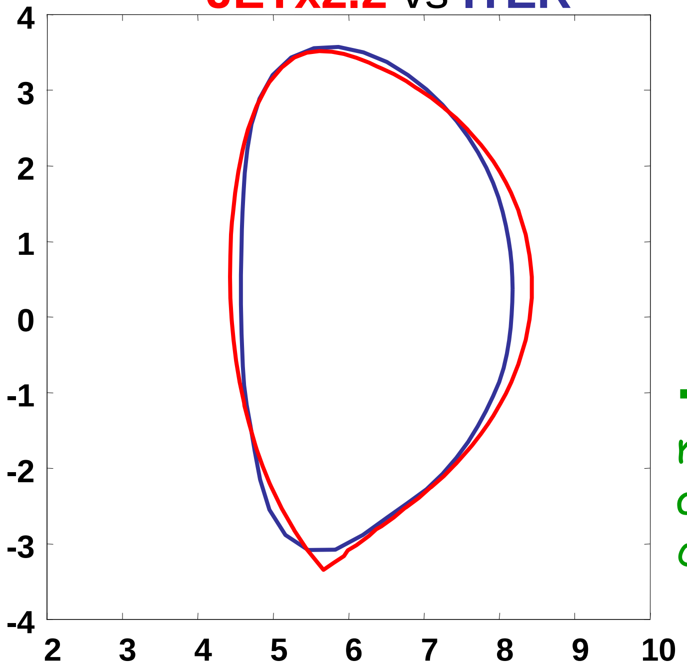
Dependence close to Bohm-like and to individual dimensionless parameter scaling

Approach to the extrapolation of the hybrid to ITER

	Step1	Step 2	Step 3
	Identity	**ρ^* step**	**$\nu_c = Rn/T^2$ step**
Ip	$a^{-1/4}$	B.a	B.a
n	a^{-2}	$B^{4/3}.a^{-1/3}$	$.a^{-2}$
T	$a^{-1/2}$	$B^{4/3}.a^{-1/3}$	$B^2.a^2$
ω_{TOR}	$a^{-5/4}$	$B^{1/3}.a^{-5/6}$	B

Joffrin EPS 2010

JETx2.2 vs **ITER**



➔ Elongation is the main difference (has a strong weight in confinement)

Constant: qcyl, I/aB, a/R, β, and Mach number

Stored energy W inferred from β.

- Scaled Te, Ti, ne profiles are given as input at each step, maintaining the dimensionless parameters as in the 0D approach.
- The plasma equilibrium is calculated for each step (identity, ρ* and ν*), and the fusion power calculated using the Bosch-Hale formulation within CRONOS.
- The standard assumption regarding radiation and Zeff for ITER are used: the discharge contains Be (2%) and Ar (0.12%) impurities, tied to the electron density profiles;
- The He profile is calculated by a 1D diffusion equation (i.e. a ratio of 5 between the He particle confinement time and the global energy confinement time. This leads to a total effective mass of 1.65. The Zeff measured in 77933 is 2.07.
- The plasma is comprised of a 50:50 D:T ratio.

	77933 (2.3T)	CRONOS + GLF23	Identity 0D	CRONOS	ρ* step 0D	CRONOS	ν* step 0D	CRONOS
a (m)	0.93	0.93	1.985	1.981	1.985	1.982	1.985	1.982
R (m)	2.905	2.905	6.2	6.199	6.200	6.199	6.200	6.199
I (MA)	2	2	1.655	1.655	6.036	6.029	9.966	9.954
B (T)	2.27	2.27	0.880	0.881	3.21	3.21	5.3	5.3
Vol (m^3)	75.78	75.75	736.82	733.835	736.82	733.83	736.82	731.135
a/R	0.320	0.320	0.320	0.320	0.320	0.320	0.320	0.320
κ	1.53	1.53	1.528	1.551	1.528	1.550	1.528	1.547
I/aB	0.947	0.947	0.947	0.948	0.947	0.948	0.947	0.948
n ($10^{\wedge 20} m^{-3}$)	0.544	0.544	0.119	0.120	0.670	0.670	0.670	0.685
Greenwald fraction	0.739	0.739	0.893	0.892	1.375	1.372	0.833	0.849
qcyl	2.582	2.582	2.582	2.614	2.582	2.615	2.582	2.610
ρ*	4.8810^{-3}	5.0410^{-3}	4.8810^{-3}	5.0710^{-3}	2.3010^{-3}	2.3810^{-3}	2.3010^{-3}	2.3710^{-3}
β	2.1610^{-2}	2.2810^{-2}	2.1610^{-2}	2.3310^{-2}	2.1610^{-2}	2.3210^{-2}	2.1610^{-2}	2.3210^{-2}
ν_c	7.8210^{-1}	7.0210^{-1}	7.8210^{-1}	6.7610^{-1}	7.8110^{-1}	6.8610^{-1}	1.0510^{-1}	9.7010^{-2}
ω_c [rd/s]	$1.16\ 10^5$	1.16105	$4.50\ 10^4$	-	$6.92\ 10^4$	-	$1.14\ 10^5$	-
W_{th} [MJ]	5.034	5.312	7.355	7.898	97.870	103.880	266.803	284.350
P_{FUS} [MW]	-	-	0.029	0.038	26.66	34	421.68	477.83
Q					0.53	0.68	8.42	9.54

- The 1.5D simulation does reproduce well each three steps of the extrapolation with the dimensionless parameters in terms of the stored energy.
- The change in collisionality has, as predicted, a strong impact on the results since it has to be decreased by a factor of 7. This emphasize the need for the scaling to confirm the exponent in ν*.
- The fusion power finally obtained in the 1D scaling would lead to a fusion gain factor of almost Q=10

Prospects for modelling

The analysis of the JET hybrid experiment is still going on and has been dealing with many modelling issues. This work has raised revealed the need for i) specific modelling ii) new physics development.

- Current profile modelling is well developed. Current ramp-up modelling has made significant progress for AT scenario in general. However in JET hybrids it is still not clear whether the n=1 continuous mode observed during this regime is not affecting the neoclassical prediction. Also there are clear evidence that the very early phase of the current development cannot be reproduced by the neoclassical theory. Both of these could have serious implication on ITER where the resistive time is much larger than the confinement time.

- Pedestal modelling has hardly started. In particular, the question is whether models can reproduce the behaviour of the pedestal pressure at high β with the power. Pedestal stability should also be undertaken.

- Computations have attempted to model the transport with ITG transport based models. It is still uncertain whether the improved confinement can be attributed directly to the Ip overshot only through s/q. It appears that the hybrid (particularly the low shapes) gradient length are larger than the ITG threshold. But the high rotation in low magnetic shear may modify the physics of stiffness as suggested by some authors (see P. Mantica). GLF23 does not reproduce the experimental data.

Prospects for modelling

- It appears essential to link the edge modelling and the core modelling. The experiments are clearly indicating a strong impact of the edge recycling condition onto the pedestal confinement with the carbon wall. This will change dramatically with a metallic wall in W and Be. For example: the particle reflection coefficients for D on W and C are about a factor 4 different.

- There are a number of indications showing that the H98y2 scaling has not the right engineering or physics parameter dependence for the hybrid scenario. This may also have some consequences on the modelling relying on this type of scaling.

- As a result, the hybrid work is also suggesting a different approach to the modelling of ITER hybrid scenario using a dimensionless physics parameter approach. This still has strong assumptions in particular on the role of rotation played on transport which is still not clarified.